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Distribution Network Capacity Assessment: Incorporating Harmonic Distortion Limits

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***Abstract*—The capacity of distributed generation (DG) connected in distribution networks is increasing as part of the drive to connect renewable energy sources. Due to widespread application of power electronic inverter interfaces, DG can inject harmonic current through the point of common connection into the upstream network. Harmonic current emission may cause voltage distortion problems when harmonic resonance exists in the network. Harmonic distortion is one area of concern for electric utilities in determining whether DG could be connected, although there are differences in utility practices in applying limits. To explore the impact of harmonic regulations on the ability of distribution networks to host DG, this work incorporates harmonic voltage constraints into an established optimal power flow (OPF) planning method. The case study shows that harmonic distortion limits have substantial impacts on the allowable penetration of DG. Furthermore, the complex interconnectivity between DG locations means that voltage, thermal and harmonic constraints have a large influence on the location preference for DG capacity.**

***Index Terms*—Harmonic analysis, distributed generation, distribution networks, optimal power flow.**

I. Introduction

DRIVEN by concern over greenhouse gas emissions and energy security, governments worldwide are aiming to increase renewable-based power production. Due to the nature of renewable resources, many generation projects will be connected to distribution network as Distributed Generation (DG). However, there are several challenges for network planners to accept DG, the most readily cited being voltage rise and power flow limitations. However, issues arising from harmonic current emissions from power electronic converters in grid-connected DGs is starting to move up the agenda as being a potential limitation on the capacity of the distribution network to accommodate DG.

Traditionally, harmonic studies in distribution network mainly focus on identification and management of harmonic voltage distortions. Well-accepted component models, simulation methods and analysis procedure has been developed. These include harmonic frequency scan [1] and harmonic power flow [2] for propagation studies as well as the design and placement of harmonic filters for mitigation. Those harmonic analysis approaches generally are based on a well-developed network, in which the entire generation capacity and load configurations are given and fixed during the period of interest. However, the rapid development of DG makes the generation capacity in distribution networks a dynamic problem with DG volumes changing substantially over the planning horizon. The harmonic simulation and filter planning methods mentioned above are not sufficient to address problems in a changing network.

There are a range of DG planning problems and studies in the literature. One major research interest focusses on how to maximize the hosting capacity while avoiding costly network upgrades. There are many approaches demonstrated that apply a range of heuristic and classical optimization methods. One class of approach makes use of optimal power flow (OPF) and models the DG capacity allocation problem while meeting the steady state constraints [3]. This method has been further extended to consider voltage step constraints [4] and security constraints [5]. The influence of various advanced control schemes, which will be incorporated in the smart grid, are studied under an adapted OPF framework [6]. There is a complete absence of methodologies that perform capacity assessments of variable renewable generation with harmonic consideration. While an optimal harmonic power flow approach is presented in [7], the objective is to use optimization method to minimize Total Harmonic Distortion (THD) by controlling taps and capacitor positions in a given system, where generation level is fixed (and therefore is not a DG planning problem).

Harmonic studies should be considered at the initial stage of network planning instead of being performed as an afterthought following 'blind' DG development. In this context, harmonic studies could be incorporated into the DG capacity evaluation. Here, an AC optimal power flow technique is adopted to maximize the DG capacity while meeting not only voltage and thermal constraints but also harmonic distortion limits. Active mitigation and advanced control scheme can also be evaluated under this extended harmonic OPF framework. The assessment of network capacity that complies with mandatory harmonic requirements in the U.K. and elsewhere would enable a fuller picture for decision making.

This paper is structured as follows: Section II summarizes harmonic modeling methods and harmonic power flow. Section III introduces a harmonic-constrained optimal power flow method to formulate the DG capacity allocation problem. In section IV, the proposed method is applied on a section of medium voltage distribution network. The results demonstrate the considerable impact of harmonic emissions on DG development, and the advantage of directly integrating harmonic assessment into OPF formulation. Finally, section V concludes the work.

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II. Formulation

A. Network Component and DG Modeling

Similar to other power system studies at the fundamental frequency, typical harmonic studies start by choosing models to present network and harmonic sources of interest. Many models have been proposed to present those linear and nonlinear components [2], [8]-[9]. Those techniques vary in terms of complexity, data requirement and solution algorithm. Specific models adopted in this paper are as follows:

1) Overhead Line and Cables: For balanced systems, overhead line and cables can be modeled as multiple nominal sections using positive sequence impedance data. According to [10], in a 50 Hz system, an error of less than 1.25% can be obtained when every single section modeled is below 10km for overhead line and 6km for cable. An equivalent model can be adopted to further improve modeling accuracy.

2) Transformers: The main characteristics of a transformer that affect harmonic flows are the short-circuit impedance and winding connection type. It is generally acceptable to model short-circuit impedance as constant R and L.

3) Passive Load: Aggregated values (MW and Mvar) for system passive load is usually readily available. Detailed composition of load is useful to characterize models properly but such data is usually not easily available. A parallel form of load representation (1) is suggested in this paper. This model can be further extended to include more detail, such as (2). However, a generally accepted model for all loads may not exist, and field measurement is needed for specific cases.

$$R_h = V^2/P X_h = V^2(h)/Q \tag{1}$$

$$R_h = V^2/P(0.9 + 0.1h) X_h = V^2(h)/Q(0.9 + 0.1h) \tag{2}$$

4) Non Linear Load: It is reasonable to present non linear loads as harmonic current sources which cause background distortion in the context of DG planning. An aggregated model is adopted here to represent different load types given their nonlinear composition and harmonic spectrum.

5) DG: Harmonic emission from DG is dependent on the specific turbine technology and internal feeder layout. However, explicit modeling is time consuming. The specific data on DG is unknown at the planning stage, and presented as an optimization variable in this paper. A simplified DG model is presented below:

$$I_{h,i} = I_h^{spectrum}(S_i^{DG}/V_i) \tag{3}$$

where $I_{h,i}^{spectrum}$ indicates the hth order current element of harmonic spectrum for DG according to the turbine technology; S_i^{DG} represents total rated DG capacity installed in bus i; V_i is nodal voltage; and $I_{h,i}$ represents the hth order harmonic current distortion injected at the DG connection point i.

IEC 61000-3-6 [11] has recommended an aggregation method for summating load harmonic current. This method can be adapted here as:

$$I_{h,i} = I_h^{spectrum} \sqrt[\beta]{\sum_{n=1}^{N} (S_i^{turbine}/V_i)} \tag{4}$$

TABLE I
SUMMATION EXPONENTS ACCORDING TO IEC 61000-3-6

Harmonic Order	β
h<5	1.0
5≤h≤10	1.4
h>10	2.0

where total DG capacity in (3) is replaced by the rated capacity of single turbine $S_i^{turbine}$. $I_h^{spectrum}$ indicates the hth order current element of typical harmonic spectrum for DG. Exponent β provides the correlation at higher frequency and recommended values are given in Table I. Applying this model for DG, say for a wind farm, will need an explicit number of wind turbines (N in the model) and accordingly results in discrete values in total DG capacity. This model is applicable for cases where the planner has a strong idea of the specific turbine type for the whole network.

It is important to point out that more sophisticated models can be used for each component when corresponding data is available. The level of detail in models will increase the complexity of the analysis, and in practice will largely decrease the feasibility of reliable data being obtained. Although the models and assumptions adopted in this paper may lead to conservative results, this is often desirable to for network planning.

B. Harmonic Power Flow

Harmonic power flow has been extensively used to quantify the distortion of current and voltage wave forms in the power network. The results are useful to determine potential resonance conditions and verify compliance with harmonic limits. Mathematically, harmonic power flow at the frequencies of interest need to solve: (5).

$$[V_h] = [Z_h][I_{h,g}] \tag{5}$$

where $[Z_h]$ is the network impedance matrix at harmonic order h; $[I_{h,g}]$ is the vector of nodal harmonic current injection of each bus; $[V_h]$ is the resulting harmonic voltage at the corresponding order. The formulation of the impedance matrix of the network and vectors of harmonic current injections is based on the selection of network component models and harmonic sources presented in the previous section.

One way of conducting harmonic assessment in DG capacity allocation studies is to neglect harmonic limits for the initial simulation. For the DG connection capacity obtained by other established optimal planning techniques, e.g., [3], or a direct proposal from DG developers, THD and individual harmonic distortion are evaluated using harmonic power flow. If the results do not comply with harmonic requirements, then the DG capacity needs to be reduced by a certain volume or a bank of filters installed for the next assessment. A similar procedure repeats until specific objectives are achieved, such as: maximum DG capacity, minimum network investment or a tradeoff between filter cost and DG capacity. This method guarantees the final result has harmonic compliance and is relatively simple in every step. However, the obligation of managing harmonics during initial DG capacity assessment creates a time-consuming repetitive procedure to check harmonic compliance. It is also not straightforward to decide how much to reduce DG capacity or where to install filters at every step, especially for multiple DG cases. Considering those shortcomings, directly embedding harmonic power flow into initial DG planning techniques is proposed in this paper.

III. Optimal power flow with harmonic constraints

OPF has been developed and extensively applied in formulating the DG capacity allocation problem [3]-[6]. Optimal potential DG penetration level can be found within the physical limitations of the network. Similar to other network characteristics such voltage and thermal limits, there are statutory requirements for harmonic distortion, indexed by total harmonic distortion (THD) and maximum distortion for each individual harmonic order (IHD). In the United Kingdom the applicable standard is Engineering Recommendation (ER) G5/4-1 [12]. When considering a connection application, DNOs in the U.K. are obliged to ensure THD and IHD compliance at connection points and all other surrounding buses, especially when high background harmonic exists in the network. As such, the integration of harmonic limits into the DG generation planning problem appears to a logical approach. The adapted AC OPF formulation is designed to maximize the total active DG capacity considering harmonic distortion limits. The objective function given as follows:

$$\max \sum_{g \in G} p_g \tag{6}$$

where P_g is active DG capacity of a set of generators G (indexed by g). It is subject to a range of constraints, which can be categorized in to two sets: one is basic network limits, the other considers harmonic distortion.

1) Basic Network Constraint:

$$\sum_{l \in L | \beta_l^{1,2} = b} p_b^L + d_b^P = \sum_{g \in G_b | \beta_g = b} p_g + \sum_{x \in G_b | \beta_x = b} p_x \tag{7}$$

$$\sum_{l \in L | \beta_l^{1,2} = b} q_b^L + d_b^P = \sum_{g \in G_b | \beta_g = b} q_g + \sum_{x \in G_b | \beta_x = b} q_x \tag{8}$$

$$V_b^- \leq V_b \leq V_b^+, \quad \forall b \in B \tag{9}$$

$$S_l - S_l^+ \leq 0 \tag{10}$$

Kirchhoff's current law as described in equation (7) and (8) ensures the active and reactive nodal power balance, where $(p,q)_b^L$ are the total power injections into lines at b and $d_b^{(P,Q)}$ are the active and reactive demands at the same bus. The allowable network voltage at each bus b and thermal constraints for each branch l are given in (9) and (10), respectively.

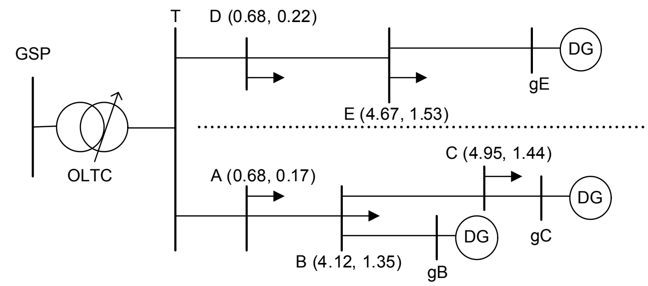

Fig. 1. 5-bus network one-line diagram during maximum load

2) Harmonic Distortion Constraints: To ensure compliance with harmonic level standards such as U.K. standard G5/4-1 following DG connection, the following harmonic constraints apply:

$$V_b^h \leq IHD^{h,+} \tag{11}$$

$$\frac{\sqrt{\sum_{h=2}^{H} (V_b^h)^2}}{V_b^1} \leq THD^+ \tag{12}$$

where V_b^h is voltage distortion at bus b for harmonic order h. As introduced in section II, V_b^h can be obtained from the harmonic power flow equation (5). When DG is modeled as a current injection source the injections are defined by the DG capacity described in both equation (3) and (4). Constraints (11) and (12) ensure that the HOPF defines DG volumes that comply with the harmonic standard.

IV. Case Study

A typical rural section of the Irish distribution network is used here as a case study [13]. While the voltage level of this network is 38kV and therefore different to U.K. 33kV practice, it has been selected as it is very simple. To illustrate the influence of harmonic constraints, the harmonic voltage planning levels for 33kV systems in the U.K. are adopted here as firm limits.

A. Distribution Network

The one-line diagram of the medium voltage distribution network is shown in Fig. 1. The corresponding line data is included in Table II. All values are in per unit (100MVA base). The feeders are supplied by one 31.5MVA 110/38kV transformer. The Grid Supply Point (GSP) voltage is assumed to be nominal. Voltage limits are taken to be ±10% of nominal. The maximum demand of the network is 15.12MW.

B. DG and Harmonic Sources

The network has three potential locations at which new wind farms can be connected: buses gB, gC and gE in Fig.1. A medium sized (0.6MW) wind turbine [14] is chosen to produce all the new power. As a widely accepted and historically encouraged operational practice, all wind farms operate at unity power factor. For harmonic analysis, wind farms are modeled as current sources. Fig. 2 presents the full frequency spectrum

TABLE II
LINE AND TRANSFORMER PARAMETERS

Line	R	X	Smax
GSP - T	-	0.25	0.315
T - A	0.0296	0.0863	0.3817
A - B	0.5941	0.6244	0.2975
B - C	0.3875	0.4072	0.1975
T - D	1.126	1.193	0.3817
D - E	0.155	0.1629	0.1975
B - gB	0.1292	0.1357	0.1975
C - gC	0.1292	0.1357	0.1975
E - gE	0.1292	0.1357	0.1975

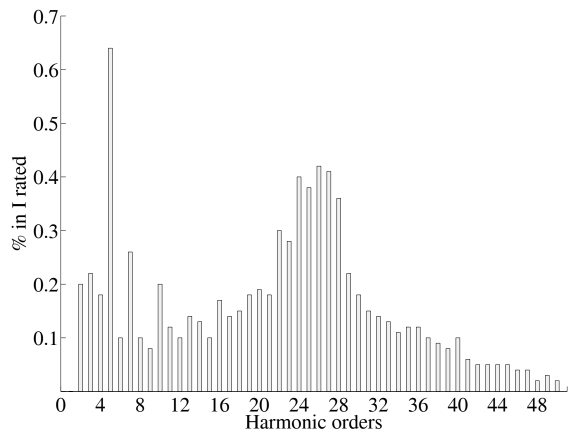

Fig. 2. Maximum harmonic current produced by wind turbine

of maximum harmonic current produced by this turbine. It extends up to 2500 kilohertz and has high harmonic distortion at lower (5th and 7th orders) and also higher frequencies (20th - 30th orders). In order to facilitate the simulation, harmonic current from all turbines is assumed to have the same phase angle to obtain the worst possible distortion, and all turbines produce balanced harmonic currents. Furthermore, all triple harmonic orders (3rd, 6th, etc.) will be eliminated by the HV-MV transformer if either side is Delta-connected and all even orders are canceled since positive and negative parts of the current waveform are almost identical. The harmonic current value of reduced order for wind farm aggregation is given in table III and will be used in the following section.

For background harmonic distortion, the 5th and 7th orders are generally most severe in the distribution system. In this paper, the voltage distortion from nonlinear load in nearby buses around the wind farms are given as firm values. Existing harmonics are set to 1.0% distortion at the 5th order and 0.5% at the 7th order. The other orders of background voltage distortion are very small and can be neglected. This data can be updated when detailed measurement is available.

C. Maximum DG Capacity

The network capability to accommodate DG depends on local load level. Under low demand levels, a given DG output means more exported power with network voltage and thermal

TABLE III
MAXIMUM HARMONIC CURRENT PRODUCED BY WIND TURBINE AND PLANNING LEVELS FOR HARMONIC VOLTAGE AT 33 & 132 KV SYSTEMS FOR REDUCED ORDERS

Harmonic Order	Harmonic Current (% in I_{rated})	Planning Level 33 &132kV (%)
5	0.64	2
7	0.26	2
11	0.12	1.5
13	0.14	1.5
17	0.14	1
19	0.18	1
23	0.28	0.7
25	0.38	0.7
27	0.41	0.66
29	0.22	0.63
31	0.15	0.6
35	0.12	0.56
37	0.1	0.54
41	0.06	0.5
43	0.05	0.49
47	0.04	0.47
49	0.03	0.46
THD		3

constraints more likely to be active. The worst-case scenarios of minimum demand and maximum generation are assumed here for determining the network's ability to accommodate DG capacity. The minimum load level is 40% of the peak demand. Another factor is the transformer tap setting in substations: to minimize voltage rise limits on the DG, the tap changer is adjusted to 1.05 p.u. to lower the secondary side voltage of OLTC between GSP and bus T.

The initial OPF evaluation of the new generation capacity that can be accommodated considers only voltage and thermal constraints and ignores harmonic constraints. The result of this is presented in column 2 of Table IV. It is evident that even under the worst-case scenario used here, the network exports power since the 42 MW total DG capacity surpasses local demand by some margin. Substantial amounts of capacity are available at buses gC and gE while a much smaller amount is possible at bus gB. This is largely due to gB sharing the same feeder as gC while gE alone is connected to a separated feeder. The constraints that actively limit the capacity at these locations are: the voltage at bus gE is at the upper voltage limit (1.1 p.u.) due to the relatively high line impedance, while there are thermal limits on both line C-gC (connecting directly to wind farm C) and the GSP transformer. The overall limit to DG capacity created by the transformer export limit means that the split in capacity between gC and gB is governed by a fairly small difference in net exports along the feeder associated with the greater impedance to reach bus gC. In other words, the additional losses that this creates delivers a higher overall net capacity so the optimization exploits this by loading bus gC to its limit before directing 'spare' capacity to bus gB. Were the feeder voltage-constrained, however, the optimization would direct more capacity to bus gB as it has a

TABLE IV
COMPARISON OF OPTIMAL DG CAPACITY RESULT BETWEEN OPF (NO HARMONICS) AND HOPF (HARMONIC CONSTRAINED)

DG bus	OPF (WM)	HOPF (WM)	Reduction (%)
gB	3.43	6.52	-90%
gC	19.75	2.32	88%
gE	18.85	4.61	76%
Total	42.03	13.44	68%

TABLE V
HARMONIC CURRENT INJECTIONS FROM THE WIND FARMS

Harmonic Order	Harmonic Current (p.u.)		
	gB	gC	gE
5	0.022	0.126	0.121
7	0.009	0.051	0.049
11	0.004	0.024	0.023
13	0.005	0.028	0.026
17	0.005	0.028	0.026
19	0.006	0.036	0.034
23	0.010	0.055	0.053
25	0.013	0.075	0.072
27	0.014	0.081	0.077
29	0.008	0.043	0.041
31	0.005	0.030	0.028
35	0.004	0.024	0.023
37	0.003	0.020	0.019
41	0.002	0.012	0.011
43	0.002	0.010	0.009
47	0.001	0.008	0.008
49	0.001	0.006	0.006

lower voltage sensitivity.

D. Compliance With Harmonic Limits

For the optimal 42 MW DG capacity identified by the non-harmonically constrained OPF, the harmonic current injections from each wind farm is shown in Table V. These are calculated by scaling the maximum harmonic current spectrum of a single turbine by the capacity at the bus. The harmonic propagation in the network is assessed by running a harmonic power flow and the results of this for THD at each bus is given in Fig. 3. For the most highly constrained wind farm at bus gE, it has the worst THD with its individual harmonics given in Fig. 4. Comparing with the planning level for harmonic voltage distortion given by ER G5/4-1 in Table III, both Fig. 3 and Fig. 4 show that the 42 MW of DG capacity suggested by the non-harmonically constrained OPF heavily violates the harmonic limits. Therefore it would not be considered as a viable option by the DNOs without sufficient harmonic filtering being commissioned.

E. Analysis with Harmonic-Constrained Optimal Power Flow

With the initial OPF failing to comply with the G5/4 harmonic limits, obtaining a planning capacity that complies with the harmonic requirements will be vital in understanding the influence of harmonics on DG capacity and the requirement for mitigation. To simplify the simulation, the relationship between harmonic injections and DG capacity at each bus is defined as a continuous value instead of a discrete one. Applying the harmonic-constrained HOPF modeling outlined in Section III, for the same wind turbine harmonic emission characteristics and the same ER G5/4-1 constraints, a revised estimate for maximum DG capacity can be gained. The results are shown in Table IV and Fig. 5. These show an overall DG capacity of 13.44MW, a two-thirds reduction from the non-harmonically constrained result. The reduction is entirely the result of the harmonic constraints becoming active and which keep the DG capacity down to maintain harmonic compliance. This differs significantly from the non-harmonically constrained case where voltage and thermal limits alone constrain DG capacity. It is also notable that the changes are non-uniform with capacity at buses gC and gE reduced by around 80% while the capacity at gB actually goes up by 90% (as indicated by a 'negative' reduction). The reason for the increase is that the large reduction in capacity at gC lowers overall harmonic levels allowing an increase at the less harmonically 'sensitive' gB. THD and IHD under this capacity allocation are also presented in Fig. 3 and 4, respectively.

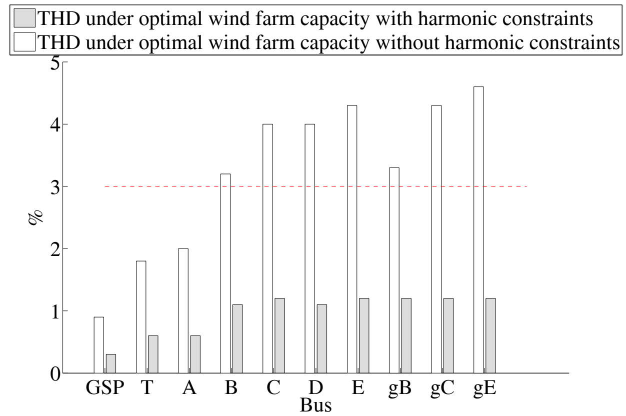

Fig. 3. Total harmonic voltage distortion at each bus under different optimal DG capacity results

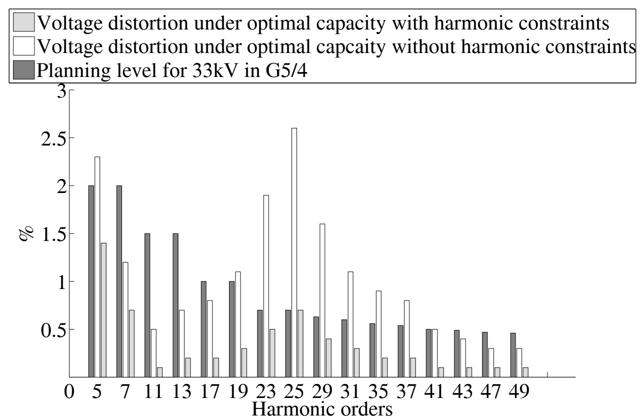

Fig. 4. Harmonic voltage distortion for individual orders at bus gE under different optimal DG capacity results

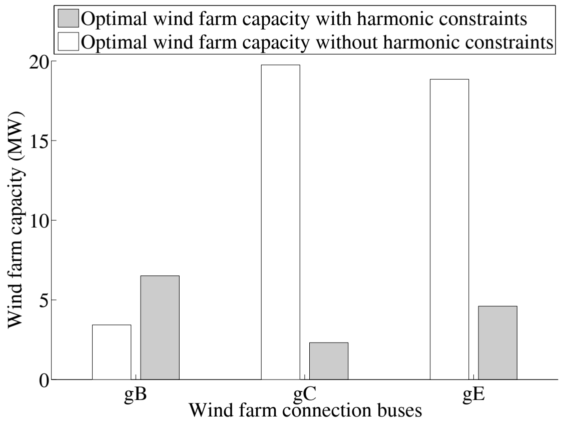

Fig. 5. Maximum DG capacity under different constraint considerations

It is clear that the results identified by the HOPF comply with harmonic limits. When inspecting the optimization result, there are active constraints associated with the 25th order harmonic at buses gB, gC and gE which all reach the 0.7% distortion limit with the latter being the binding constraint that prevents the network from accommodating more capacity. This reduction reflects the importance of introducing sufficient harmonic filter facilities, and with the 25th order harmonic treated as a priority.

F. Discussion

As mentioned earlier, one option for defining DG capacities that comply with harmonic limits is to undertake an indirect iterative process of: (1) obtaining DG capacity from the voltage and thermally constrained-OPF analysis (Section IV-C); (2) running harmonic power flow assessment; and (3) reducing DG capacity to comply with the harmonic limits. On the face of it this is a straightforward process, but in practice it is more difficult to ensure optimality. As Table IV shows the proportional changes between the initial OPF and final HOPF capacities at each bus are not the same and in the case of bus gB actually increase after considering harmonics. Therefore, it is inappropriate to define the same reduction ratio for the repeating procedure. As such a more direct method that explicitly links DG capacity and harmonics is more effective in handling the complex interaction between different DG in terms of harmonic emissions as well as impact on voltage and thermal constraints.

A significant reduction of the hosting capacity of the network is shown after considering harmonic limits. The simulation using worst-case scenarios and also strict compliance with the ER G5/4-1 standard contribute to this result. In practice, the harmonic requirement is not as strongly enforced as voltage variation and thermal rating limits, and the worst-case scenario may infrequently happen. As a result there could be more 'space' for accommodating DG according based on the actual connection agreements between developers and DNOs.

Harmonic filters can provide a mitigation solution to facilitate DG integration. The cost of filters requires appropriate placement and tradeoff analysis and an optimization method is useful in this respect. The active constraint found in the HOPF analysis can indicate the order(s) at the buses that constrains DG. It can also be used to check the required level of mitigation required, at which point the active constraint will switch to other network constraints instead of harmonics.

V. Conclusion

New DG development in distribution networks has inherent constraints such as energy resource availability, transmission capacity, and therefore it is of value for DNOs to access the extent to which their networks are capable of connecting new generation. In this context, the more constraints that the simulation modeling can take into account, the more applicable the results are.

In this paper, harmonic distortion limits are introduced as new constraints into the study of the ability of distribution networks to accommodate DG. The harmonic propagation results following a snapshot scenario optimization suggests severe violation of statutory harmonic requirements, and potentially impractical DG capacity planning results. Directly incorporating THD and individual harmonic planning level limits into the optimization of DG capacity sees a substantial reduction in connectable capacity.

Further work is required to improve and validate the harmonic emission model of DG presented here. Nonlinear load in the distribution network is another main source for voltage distortion which will also need to be measured and modeled in detail. When harmonics highly influence DG capacity limits, harmonic filter will need to be installed as a mitigation solution and the model here can be the basis for cost-benefit studies. It will also be necessary to carry out the analysis using larger, more realistic distribution networks.

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